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Seeking Experimental Probes of String Unification*

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Abstract

A general prediction of string unification is the existence of exotic states with fractional charges under the free unbroken Abelian generators of the underlying GUT symmetry. Such states may be long–lived due to the existence of weakly broken gauge, or local discrete, symmetries, and may serve as experimental probes of string theory in forthcoming cosmic ray and dark matter experiments.

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String theory is the leading candidate for a theory of quantum gravity. Although in itself an important achievement, the primary challenge facing string theory is to prove its relevance for experimental data. On the other front, the Standard Particle Model successfully accounts for all observations in contemporary accelerator and non–accelerator experiments. However, despite this enormous success the Standard Model is not satisfactory as it leaves many issues unresolved, including: the origin of the particle spectrum and interactions; the experimental verification of the Higgs sector and its incorporation in a fundamental theory; finally the framework of point quantum field theories, on which the Standard Model is based, is not compatible with quantum gravity. Synthesizing these two fronts is the domain of string phenomenology. Superstring phenomenology serves the dual purpose of developing the tools and methodology to confront string theory with the experimental data, and of providing the structures and framework to try to understand how the building blocks of the Standard Model may arise from a consistent theory of quantum gravity. In this respect, while much effort is being devoted to understanding the structures of the Standard Model in the context of various schemes beyond the Standard Model, these attempts are in general deficient in the sense that they assume additional structures for which there is no observational need or evidence. String phenomenology on the other hand has the advantage that the additional structures are not added injudiciously, but are rather imposed by the consistency of the theory. One should then make the most strenuous effort to derive from string theory solely the observed Standard Model physics. Once successful, any left–over can then truly be considered as a prediction of the theory, or of the specific string model.

In the past we discussed various possible signatures of string theory, which included: specific patterns of the supersymmetric spectrum [1]; extra stringy Z''s [2]; and stringy dark matter candidates [3]. In this paper we discuss the availability of string theory candidates to explain the Ultra High Energy Cosmic Ray (UHECR) events beyond the Greisen–Zatsepin–Kuzmin (GZK) cutoff [4]. In this respect one of the most fascinating unexplained experimental observations is that of Ultra High Energy Cosmic Rays with energies in excess of the Greisen–Zatsepin–Kuzmin (GZK) bound [5]. There are apparently no astrophysical sources in the local neighborhood that can account for the events. The shower profile of the highest energy events is consistent with identification of the primary particle as a hadron but not as a photon or a neutrino. The ultrahigh energy events observed in the air shower arrays have muonic composition indicative of hadrons. The problem, however, is that the propagation of hadrons over astrophysical distances is affected by the existence of the cosmic background radiation, resulting in the GZK cutoff on the maximum energy of cosmic ray nucleons $E_{\rm GZK} \leq 10^{20}$ eV. Similarly, photons of such high energies have a mean free path of less than 10Mpc due to scattering from the cosmic background radiation and radio photons. Thus, unless the primary is a neutrino, the sources must be nearby. On the other hand, the primary cannot be a neutrino because the neutrino interacts very weakly in the atmosphere. A neutrino primary would imply that the depths of first scattering would be uniformly distributed in column density, which is contrary to the observations.

One of the most intriguing possible solutions is that the UHECR primaries originate from the decay of long–lived super–heavy relics, with mass of the order of 10^{12-15} GeV [6]. In this case the primaries for the observed UHECR would originate from decays in our galactic halo, and the GZK bound would not apply. Furthermore, the profile of the primary UHECR indicates that the heavy particle should decay into electrically charged or strongly interacting particles. From the particle physics perspective the meta–stable super–heavy candidates should possess several properties. First, there should exist a stabilization mechanism which produces the super–heavy state with a lifetime of the order of $10^{17}s \leq \tau_X \leq 10^{28}s$, and still allows it to decay and account for the observed UHECR events. Second, the required mass scale of the meta–stable state should be of order $M_X \sim 10^{12-13}$GeV. Finally, the abundance of the super–heavy relic should satisfy the relation $(\Omega_X/\Omega_0)(t_0/\tau_X) \sim 5 \times 10^{-11}$, to account for the observed flux of UHECR events. Here t_0 is the age of the universe, τ_X the lifetime of the meta–stable state, Ω_0 is the critical mass density and Ω_X is the relic mass density of the meta–stable state.

As we discuss here, superstring theory inherently possesses the ingredients that naturally give rise to super–heavy meta–stable states. The stabilization mechanism arises in string theory due to the breaking of the non–Abelian gauge symmetries by Wilson lines. This gives rise to states in the string spectrum that carry fractional charges under the unbroken free $U(1)$ generators in the Cartan subalgebra of the original non–Abelian gauge symmetry. The most apparent and well known such example is that of states that carry fractional electric charge. However, as we discuss further below, string models may also contain exotic states that carry the standard Standard Model charges, but carry fractional charge under an orthogonal free Abelian subgroup of the original non–Abelian gauge symmetry. Such states cannot fall into representations of the original unbroken non–Abelian gauge group. Furthermore, they arise in string theory due to the nontrivial topology of the string and the breaking of the non–Abelian gauge symmetry by Wilson line. Thus, such states in general do not arise in ordinary Grand Unified Theories, in which the non–Abelian gauge symmetries are broken by the Higgs mechanism. The existence of fractionally charged states can be regarded as a general consequence of string unification, or as a very specific string prediction. The question, however, is how can such states reveal themselves in contemporary experiments.

The existence of fractionally charged states in string theory obviously gives rise to a stabilization mechanism. The states that carry fractional electric charge cannot decay due to electric charge conservation. However, also those exotic states that carry standard Standard Model charges but fractional $U(1)_{Z'}$ charge may be stable. This arises if the Standard Model states and the Higgs multiplets are identified with representations of the original GUT theory. In this case even after the breaking of $U(1)_{Z'}$ by a Higgs VEV there remains a discrete symmetry which forbids the decay of the exotic state to the Standard Model states. In practice it is sufficient to demand that vevs which break the discrete symmetry are sufficiently small. The super–heavy states can then decay via the nonrenormalizable operators

$$\frac{\langle V_1 \quad \cdots \quad V_N \rangle}{M_S^{N-3}} \quad ; \quad M_S \sim 10^{17-18}\mathrm{GeV} \tag{1}$$

which are produced from exchange of heavy string modes. The lifetime of the meta–stable relic is then given by

$$\tau_X \;\approx\; \frac{1}{M_X}\left(\frac{M_S}{M_X}\right)^{2(N-3)} \tag{2}$$

Additionally, string theory may naturally produce mass scales of the required order, $M_X \approx 10^{12-13}$GeV. Such mass scales arise due to the existence of an hidden sector which typically contains non–Abelian $SU(n)$ or $SO(2n)$ group factors. Thus, the mass scale of the hidden gauge groups is fixed by the hidden sector gauge dynamics. Therefore, in the same way that the color $SU(3)_C$ hadronic dynamics are fixed by the boundary conditions at the Planck scale and the $SU(3)_C$ matter content, the hidden hadron dynamics are set by the same initial conditions and by the hidden sector gauge and matter content, $M_X \sim \Lambda_{\text{hidden}}^{\alpha_s, M_S}(N, n_f)$. Finally, the fact that $M_X \sim 10^{12-13}$GeV implies that the super–heavy relic is not produced in thermal equilibrium and some other production mechanism is responsible for generating the abundance of super–heavy relic. This may arise from gravitational production [7] or from inflaton decay following a period of inflation.

Fractionally charged states are generic in the perturbative heterotic string theory. We may however question whether this will remain a general consequence of string theory also in the nonperturbative regime. Naturally a definite answer to this question is not possible at present due to the non–existence of a nonpurterbative formulation of string theory. However, we may try to contemplate the understanding of string theory that emerges from string dualities. In this picture, as depicted in fig. (1) the different string theories, including eleven dimensional supergravity are perturbative limits of a more fundamental theory, dubbed M–theory. In this context, we may question as well the utility of any of the perturbative string limits to try to capture our experimental reality. One may put the bar a bit higher and question the use of string/M theory in the first place. Clearly, the fact that string/M theory provides a self–consistent framework for quantum gravity does not yet imply its relevance for physical reality, and indeed alternative approaches do exist [8]. We may furthermore infer from the approach of ref. [9] to quantum mechanics that basic particle properties may fundamentally be seen to arise differently from the conventional Hilbert space constructions, which underly all of the string theories. Thus, it may eventually be revealed that the Hilbert space construction, and with it the notion of a particle with definite properties, is an effective description, rather than a fundamental one. With these issues in mind, then what sense is there in seeking

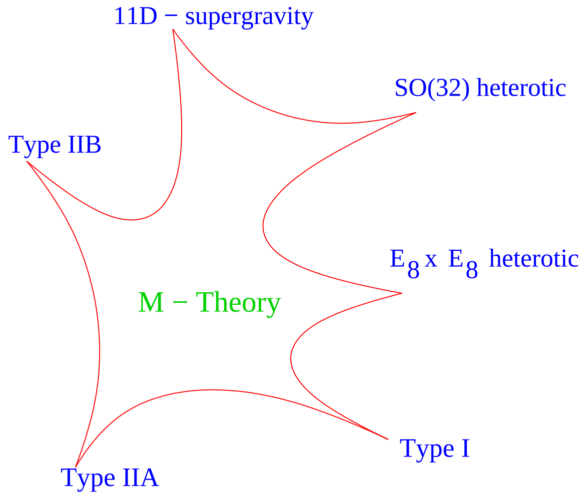

Figure 1: M–theory picture of string theory

experimental probes of string theory, in general, and in a specific perturbative limit, in particular. To formulate a logical sequence we must go back and examine the premise of the Standard Model. The Standard Particle Model is the objective reality as we perceive it in contemporary experiments. The technological and sociological complexity of the collider experiments by which the Standard Model was revealed represent the pinnacle of scientific achievement. The Standard Particle Model is composed of three group factors $SU(3)_C \times SU(2)_L \times U(1)_Y$, three generations of chiral matter states that carry charges under the three group factors, and a Higgs sector. The Higgs sector has not yet been discovered experimentally and its elucidation is perhaps the most burning question in basic physics. However, examining the matter sector alone we note that, in the process of its experimental discovery, the gauge quantum numbers are in fact free experimental parameters. A naive count therefore gives $3 \cdot 3 \cdot 6 = 54$ free parameters, counting the 3 group factors, three generations, and the 6 $\{Q, L, D, U, E, N\}$ states in each generation, including the right–handed neutrino. Now, a true miracle of the Standard Particle Model is the fact that each generation fits into a single representation of $SO(10)$. From the parameter account this miracle entails the reduction of the number of free gauge quantum parameters from 54 to 3! A true miracle indeed! One may therefore take the view that the essence of the Standard Model is its embedding in a Grand Unified Theory! The GUT framework, however, provides only partial unification, and cannot explain the origins of flavor, hierarchy and gravity, which are clearly additional features of the objective reality. String theory provides the only currently available self–consistent theoretical framework in which these additional structures are unified. Therefore, at present string theory provides the only available tool at our disposal to explore the unification of flavor, hierarchy and gravity.

None of the perturbative string theories is more fundamental than the others.

This conclusion is clear from the mere fact that the perturbative string theories are perturbative, and do not follow from a fundamental physical principle. The utility of the different string theories is precisely as the perturbation theory of the more fundamental structure, which we may call M–theory. Hypothesizing that the true vacuum of the world does indeed lie somewhere in the region enclosed in fig. (1), the different perturbative limits probe different properties of the true vacuum. From our objective reality, as perceived by the Standard Model, we may hypothesize that a fundamental feature of the true vacuum is the embedding of the Standard Model multiplets in $SO(10)$ representations. The only perturbative limit which enables this embedding is the perturbative heterotic string limit. This indicates that if we choose to preserve the $SO(10)$ GUT embedding of the Standard Model spectrum then the perturbative limit that we should use is the heterotic string limit, whereas the other perturbative limits may be more useful to learn about other properties of the true vacuum. In this limit the $SO(10)$ symmetry is broken by Wilson line directly at the string level, rather than by a Higgs VEV in the effective low energy field theory. The string spectrum then will necessarily contain exotic states which fractional charges under the unbroken free $U(1)$'s in the Cartan sub–algebra of $SO(10)$. In this effective perturbative limit of the true vacuum such states are realized and are endemic. The existence and self–consistency of the perturbative description itself then indicates that such states are realized and may have experimental manifestation. Following the lead suggested in ref. [9], and therefore keeping in mind that the notion of a particle with definite properties is in any case an effective description, how and whether such states will appear in the nonpurterbative limit is immaterial.

The requirement that a realistic string vacuum admits the $SO(10)$ embedding of the three chiral generations is highly restrictive. The reason being that string vacua typically contain additional $U(1)$ generators, beyond those present in the Standard Model or its GUT extensions. This facilitates finding combinations of the $U(1)$ currents which reproduce the correct Standard Model hypercharge assignments. The expense is that the $SO(10)$ embedding and the canonical normalization of the weak hypercharge is lost. Consequently there exist many models that do not admit the $SO(10)$ embedding [10], whereas those that possess the $SO(10)$ embedding are less abundant. A class of string models that possess the $SO(10)$ embedding are those constructed in the free fermionic formulation. These models correspond to $Z_2 \times Z_2$ orbifold compactification at the free fermionic point in the Narain moduli space, augmented with Wilson lines that break the $SO(10)$ symmetry. The models themselves have been built in the free fermionic language [11], but can be translated to orbifold language. The general structure of these models has been amply reviewed in the past and we refer interested readers to the original literature [12] and the reviews for the details [13]. Here we recap the main structure which is relevant for our discussion of the meta–stable superheavy string relics.

The models can be seen to be constructed in two stages. The first stage corresponds to the so–called NAHE set of boundary condition basis vectors, typically denoted by $\{\mathbf{1}, S, b_1, b_2, b_3, X\}$ [13], and corresponds to the $Z_2 \times Z_2$ orbifold compactification [14]. The three twisted sectors of the $Z_2 \times Z_2$ orbifold produce in these models the three Standard Model chiral generations. The untwisted sector produced the gravity and gauge multiplets and, plus one additional sector, produces also the Standard Model Higgs multiplets. In addition the orbifold spectrum contains hidden sector matter states that transform in the vectorial representation of the hidden $SO(16)$ subgroup. This hidden matter arises in the string models due to the breaking pattern $E_8 \times E_8 \;\rightarrow\; SO(16) \times SO(16)$ by a GSO projection, which also breaks $E_6 \;\rightarrow\; SO(10) \times U(1)$. At the level of the NAHE set the observable GUT symmetry is $SO(10)$, with 24 chiral super–generations in the chiral 16 representation of $SO(10)$.

The second stage consists of adding to the NAHE set three additional boundary condition basis vectors, typically denoted by $\{\alpha, \beta, \gamma\}$, which correspond Wilson lines in the orbifold language. These additional basis vectors break the $SO(10)$ symmetry to one of its subgroups, where the cases of $SU(5) \times U(1)$, $SO(6) \times SO(4)$ or $SU(3) \times SU(2) \times U(1)^2$ have lead to quasi–realistic models. At the same time the additional basis vectors reduce the number of twisted chiral generations to three generations, one from each of the twisted sectors b_1, b_2 and b_3. The important point to emphasize from the discussion thus far is that all the states which are identified with the Standard Model states arise from the orbifold sectors. All these states are $SO(10)$ representations, which are reduced into representations of the final unbroken $SO(10)$ subgroup. In this construction, therefore, the Standard Model admits the $SO(10)$ embedding, and the weak–hypercharge has the canonical $SO(10)$ normalization.

The realistic free fermionic models provide an arena in which many of the phenomenological issues pertaining to the Standard Model as well as those pertaining to supersymmetric unification can be examined from the view point of perturbative quantum gravity. We refer interested readers to the previous review articles and references therein [13]. The issues studied include: top quark mass prediction; fermion masses and mixing; proton stability and neutrino masses; gauge coupling unification; squark degeneracy; derivation of string models with solely the MSSM spectrum in the low energy effective field theory. These achievements demonstrate the utility of the free fermionic models as a laboratory to study these phenomenological issues in the context of a potentially fundamental theory. Alternatively the models provide the means of connecting string theory with experimental data.

We now turn to the discussion of the exotic states as a possible experimental probe of string theory. In addition to the "standard" spectrum from the orbifold sectors, there exist in the heterotic–string models "exotic" spectrum which cannot fit into $SO(10)$ multiplets. This spectrum arises from sectors which contain the Wilson line breaking sectors, and produces the exotic matter in vector–like representations. Their interaction terms in the superpotential are obtained by calculating the correlators between vertex operators. The non–vanishing correlators must be invariant under all the symmetries and the string selection rules. The exotic "Wilsonian" matter states appear in the free fermionic models in vector–like representations, and obtain mass terms from cubic level or nonrenormalizable terms in the superpotential. In general, unlike the "standard" spectrum, the "exotic" spectrum is highly model dependent. We can however classify the exotic matter according the patterns of the $SO(10)$ symmetry breaking by the specific sectors. The $SU(5) \times U(1)$ and $SO(6) \times SO(4)$ type sectors produce states with electric charges $\pm 1/2$. Similar to QCD the fractional charges may be confined by a hidden sector gauge group [15]. The resulting integrally charged bound states then produce meta–stable superheavy matter. Similar to QCD the mass scale of the bound states is fixed by the initial conditions at the unification scale, and by the gauge and matter content of the confining gauge groups. Mass scales of required order of 10^{12-13}GeV appear very naturally in realistic heterotic string models due to the existence of the hidden sector. The fractionally charged constituents are stable due to electric charge conservation, and the bound states may decay through the nonrenormalizable terms (1). Depending on the order N, the lifetime from Eq. (2) may be in the appropriate range to account for the flux of observed UHECR events above the GZK cutoff [15]. However, in addition to the lightest neutral bound states there exist in this model also long lived meta–stable charged bound states, whose abundance is comparable to that of the neutral states [16]. Constraints on the abundance of stable charged heavy matter then places an additional constraint on the lifetime of this form of UHECR candidates [16].

In addition to the fractionally charged states, the free fermionic standard–like models contain states, which arise from $SU(3) \times SU(2) \times U(1)^2$ type sectors, and carry the regular charges under the Standard Model, but carry "fractional" charges under the $U(1)_{Z'} \in SO(10)$ symmetry. These states can be color triplets, electroweak doublets, or Standard Model singlets and may be good dark matter candidates [3]. The meta–stability of this type of states arises because of their fractional $U(1)_{Z'}$ charge. Namely, the fact that the Standard Model states possess the $SO(10)$ embedding, implies that there exist a discrete symmetry which protects the exotic matter from decaying into the lighter Standard Model states. We must additionally insure that the $U(1)_{Z'}$ symmetry breaking VEVs, break the discrete symmetry sufficiently weakly. The uniton is such a color triplet that has been motivated to exist at an intermediate energy scale due to its possible role in facilitating heterotic–string gauge coupling unification. It forms bound states with ordinary down and up quarks. The mass of the uniton is generated from nonrenormalizable terms and can be of order 10^{12-13}GeV, as required to explain the UHECR events. Additionally, if the uniton is to contribute substantially to the dark matter, the lightest bound state must be neutral and the heavier charges states must be unstable. However, contrary to the case of the fractionally charged states, in uniton charged bound states can decay through $W^{\pm}$ radiation of the ordinary quark with which it binds. Lastly, the free fermionic Standard–like models contains Standard Model singlets that carry fractional $U(1)_{Z'} \in SO(10)$ charge. Such states may be semi–stable provided that the discrete symmetry is broken sufficiently weakly. Moreover, similar to the states with fractional electric charge, they may transform under a hidden sector non–Abelian gauge group and may their mass scale may therefore be fixed by the confining hidden sector scale. Being neutral, they provide ideal dark matter and UHECR candidates.

Superstring models provide a variety of candidates with differing properties that may account for the observed UHECR events. The phenomenological challenge is to develop the tools that will discern between the different candidates, by confronting their intrinsic properties with the observed spectrum of the cosmic ray showers. The UHECR data, however, opens up new probes to the GUT and string scale physics. The point is that in the analysis of the decay products of the meta–stable states one must extrapolate measured parameters from the low scale, at which they are measured, to the high–scale of the hypothesized meta–stable state. In this extrapolation, which covers more than 10 orders of magnitude in energy scales, one must make some judicious assumptions in regard to the particle content. Thus one may hope that the extrapolation itself will enable to differentiate between different assumptions in regard to the physics in the extrapolation range. This methodology is very similar to that employed successfully in the case of gauge coupling unification in supersymmetric versus non–supersymmetric cases. There the motivation for the extrapolation arises from the hypothesis of unification and one can show that it is consistent only if one includes the supersymmetric spectrum. Similarly, in the case of the of the UHECR events, the motivation for the high scale are the events themselves and the possibility to explain them with the super–heavy meta–stable matter. The extrapolated parameters are the QCD fragmentation functions and similarly one must include in the evolution whatever physics is assumed to exist in the desert. In ref. [17] supersymmetric fragmentation functions were developed for this purpose. Furthermore, such functions may also be used in the analysis of the cosmic rays showers, which arise from the collision of the primaries with the atmosphere nuclei at a center of mass energies of order $\sim$ 100TeV. Most exciting, however, is perhaps the fact that the forthcoming Pierre Auger and EUSO experiments will explore precisely the physics of the UHECR above the GZK cutoff! The hypothesized meta–stable super–heavy string relics may then serve as experimental probes of the string physics, provided that we are able to develop the phenomenological tools to decipher their predicted properties, such as their fractional electric or $U(1)_{Z'}$ charge!

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